U.S. NAVAL RESEARCH LABORATORY

Power Electronic Materials and Devices: Silicon to Diamond

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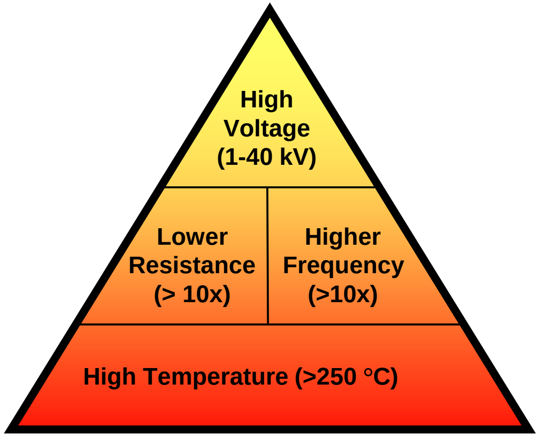
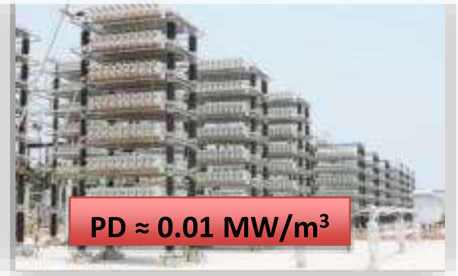
Electronics Science and Technology Division
Power Electronics & Advanced Materials Branch

Navy Power Electronics Requirements

Major Device Class			Applications
Voltage	Power	Junction Temperature	
600-1200V	10-500 kW	250-300°C	F-35 Joint Strike Fighter More Electric Aircraft
288-900V	200-300kW	150-250°C	4 ton wheeled vehicle
1200-1700V	700-900kW	150-250°C	15 ton combat vehicle, also* (*ship service ≈ 100-250kW, 150°C, submarine > 150°C)
6.5-11kV	80MW	150°C	Two-level inverter for Electromagnetic Arrest and Launch Three-level inverter for 4.16kVAC distribution for destroyer Five-level inverters for 13.8kVAC distribution for carriers
11-20kV	> 80MW	150°C	12kV DC distribution distribution Three-level inverter for 13.8kVAC distribution for carriers
12-25kV		250-400°C	Pulsed Power Switch for EM Railgun and Active Armor



HVDC VSC (±400 kV, 500 MW) in remote SUBURBAN areas



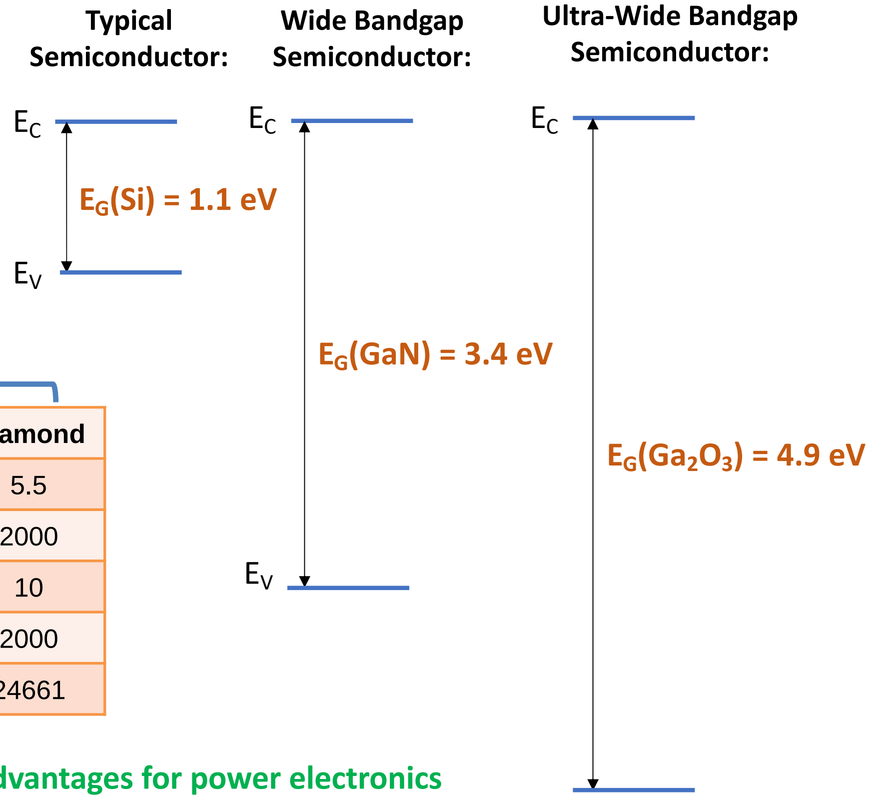
Future Naval MVDC Systems

PD > 1 MW/m³

Power Density is the critical parameter for DoD systems!

New Materials for Future Power Devices

- Power devices need to block **high voltages**, then have **low resistance** when conducting in the ON-state
- Semiconductor's wider bandgap → higher blocking voltage
- However… cannot simply use glass to make a power device, because you can't turn it ON. (Need a semiconductor that can be doped n-type, p-type, or preferably both)



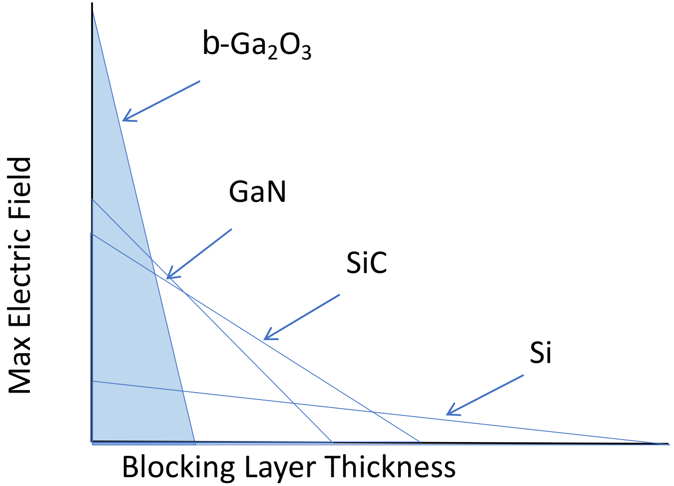
	Si	4H-SiC (WBG)	GaN (WBG)	β-Ga_2O_3 (UWBG)	Diamond (UWBG)
Bandgap (eV)	1.1	3.26	3.4	4.9	5.5
Electron Mobility (cm^2/V-s)	1350	900	1200	300	2000
Critical Field (MV/cm)	0.3	2.5	3.3	8	10
Thermal Conductivity (W/m-K)	130	370	130	30	2000
Baliga Figure of Merit	1	160	870	3444	24661

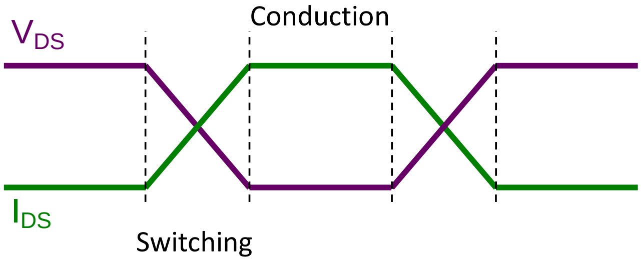
Devices made with WBG/UWBG materials offer enormous advantages for power electronics

How WBG/UWBG Devices Improve SWaP

How WBG/UWBG semiconductor devices can improve size, weight, and power (SWaP) of systems:

- WBG/UWBG devices enable thinner blocking layers
  - Lower ON-resistance
  - Shorter transit time (time is takes for an electron to cross the device)
- More compact power systems
  - Lower conduction losses
  - Lower switching loss → Higher switching frequency
  - Smaller volume, Volume ~ 1/frequency





Total Power Losses = Switching Losses + Conduction Losses

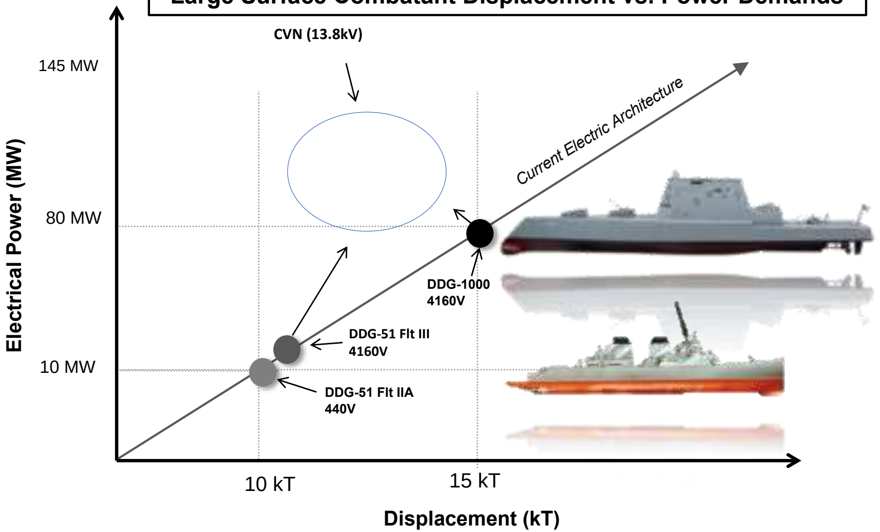
Conduction power loss ~ R_{ON} ~ $1/(\mu E_{max})$

Switching power losses ~ R_{ON} x C_{in}= $1/f_B^3$

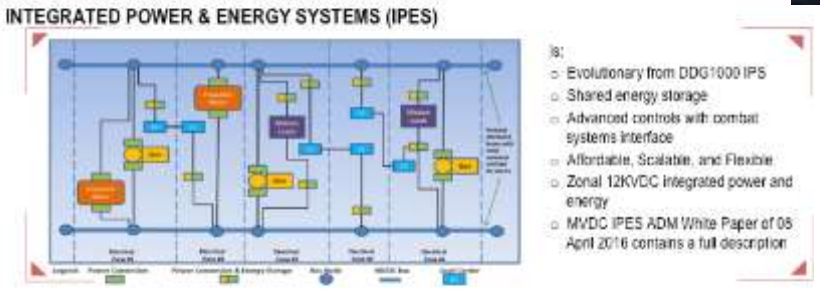
System Level Impact: Compact Power Conversion for improved SWAP-C (Vol. ~ $1/f_{SW}$)

Shipboard Power Conversion

Large Surface Combatant Displacement vs. Power Demands



Future Power Payloads:
- Future Radar
- Rail Gun
- Hybrid propulsion
- Solid State Laser
- Future EW systems
- Future Illuminator
- Hull Sensor
- Vertical Launch System
- Laser Weapon System
- Multi-Function Towed Array
- Etc.

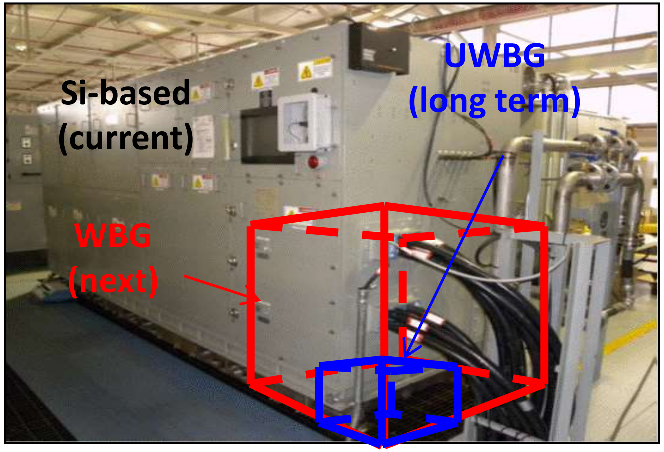


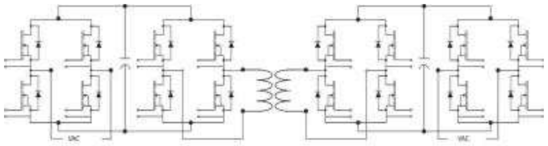
Compact high voltage power systems are required for future ship demands → WBG/UWBG are advantageous for high voltage components

20kV switches needed for 13.8kV AC Power Distribution

The LRU Concept

DDG 1000 Power Control Module





PEBB1000 Vision:
- All 4 H-bridges
- No External Water Connectors
- Simplified Electrical and Mechanical Connections
- Sailor Safe
- Hassel Free Installation and Maintenance

Enabled by:
- High voltage/high speed WBG switches
- High power/high frequency magnetics
- Advanced control architectures

UWBG-based PEBB could:
- Require 10X fewer LRUs for the same power system
- Output 10X more power for the same module size
- Some combination of the two (optimization of space and power handling)

Magnetics in Power Conversion

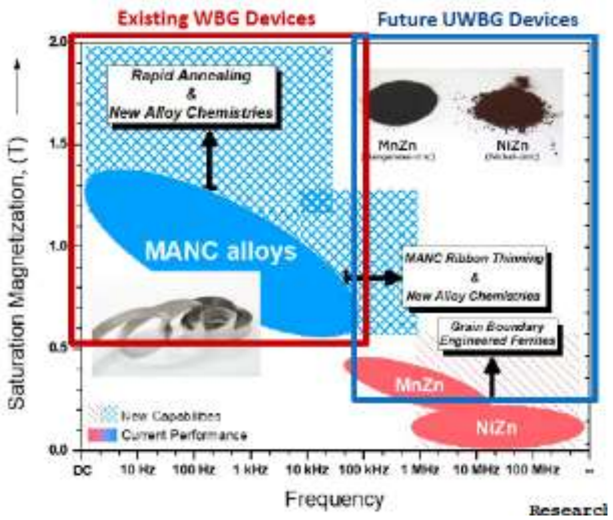
Magnetics: key factor determining size, weight, and efficiency of power converters

Multiple functions and requirements

- Transformers (high permeability): voltage and current scaling and sensing
- Inductors (low permeability): energy storage, circuit resonance, filtering, current limiting

WBG devices can be accommodated with improvements to existing materials

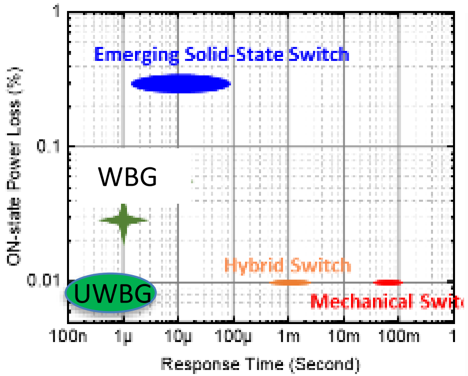
UWBG devices require new materials

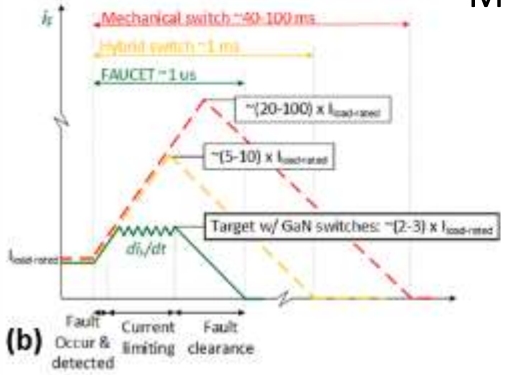


New materials research and advanced manufacturing strategies are required!

Solid State Circuit Breaker

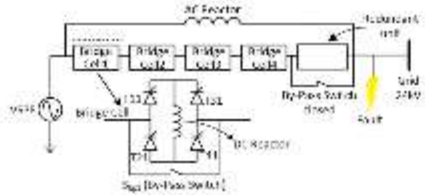
DC power systems to not have a natural “zero crossing” for rapid fault detection and clearing – increased likelihood of arcing, necessitating new protection architectures





Mechanical switch (current)

Solid-state protection (future)



WBG/UWBG-based circuit breakers or fault current limiters can turn off MV systems >100X faster than SOTA with lower loss

	Die Size (cm^2)	BV (V)	I_{ON} (A)	V_{ON} (V)	R_{ON}*A
Si IGBT	1.36 X 1.36	6,500	25	4.2	311
SiC MOSFET	0.81 X 0.81	10,000	20	7	230
GaN SHJ	1.16 X 1.16	10,000	100	2.45	33

Topic 1: Device-Scale Thermal Management

Thermal Management of GaN Electronics

Thermal Characterization:

In-house:

- micro-Raman thermography
- Infrared Imaging
- Steady-state thermoreflectance
- Transient thermoreflectance

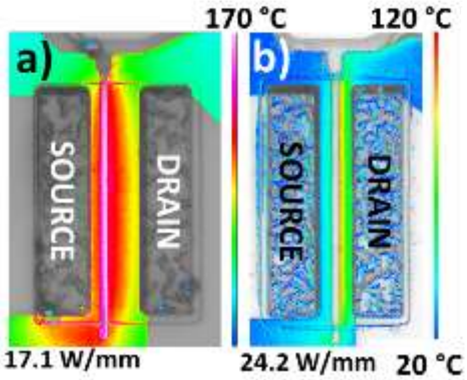
In collaboration:

- Gate resistance thermography
- Scanning Thermal Microscopy

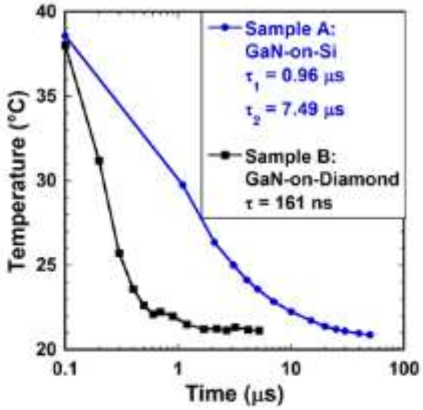
Optimization via Modeling:

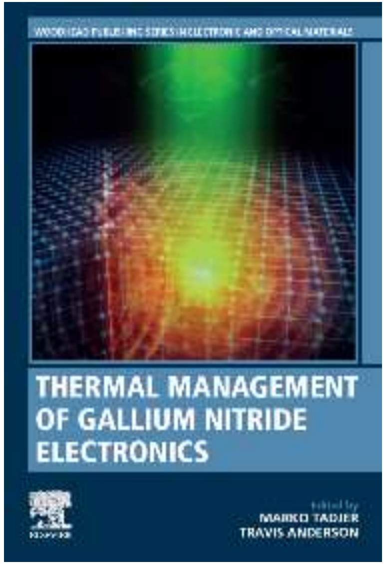
- Understanding of localized effects that are difficult to characterize experimentally
- Band structure
- Electric field spreading
- Temperature depth profiling
- Thermal interface modeling

Steady State TRI



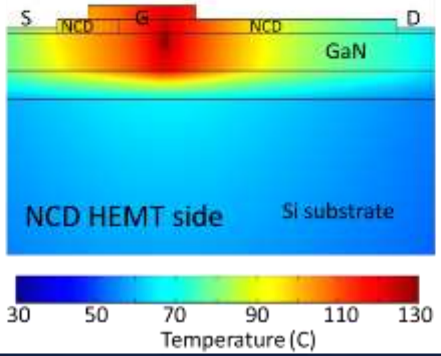
Transient TRI



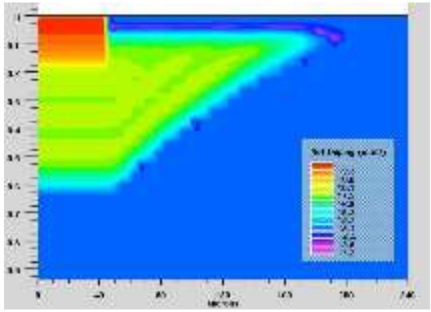


Tadjer and Anderson, Ed., Elsevier 2022.

3D GaN HEMT model



Edge Termination



NRL Diamond Growth Capability

5 Microwave Plasma CVD Reactors for growth + 1 for surface hydrogenation

	MW CVD Reactors	Location		Point of Use Purification		Impurity		SCD	Pyrometry	NCD	Reflectivity	PCD (Thick Film)
		A11	207	H2	CH4	B	N					
1.	5 kW ASTEX	✓		✓	✓*	✓	-	c				✓
2.	1.5 kW ASTEX	✓		✓	✓*	✓	-			✓	✓	c
3.	6 kW CTS	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
4.	5 kW IPLAS		✓	✓	✓	-	-			✓	✓	c
5.	1.5 kW ASTEX		✓	✓	✓	-	✓	✓	✓			
6.	1.5 kW ASTEX**		✓	✓	-	-	-		✓	c		

✓ — current configuration

✓* — to be installed equipment on site

c — capability, but not current configuration

** — dedicated to surface hydrogenation

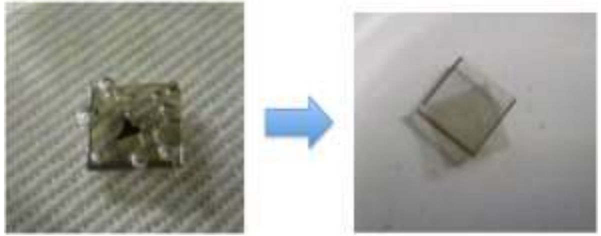
Microwave Plasma Chemical Vapor Deposition

IPLAS
5 kW

ASTEX
one 5 kW unit
three 1.5 kW units

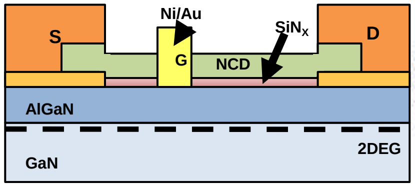
Carat System (CTS)
6kW

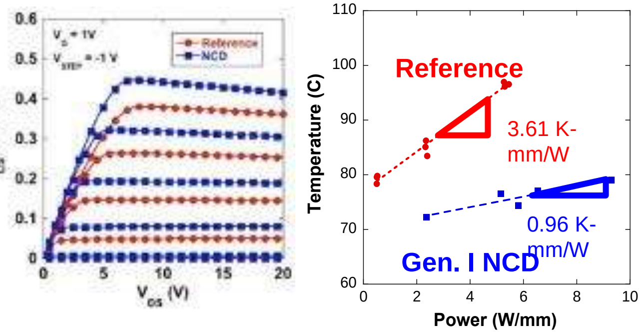
Electrochemical etching process for epitaxial film lift-off



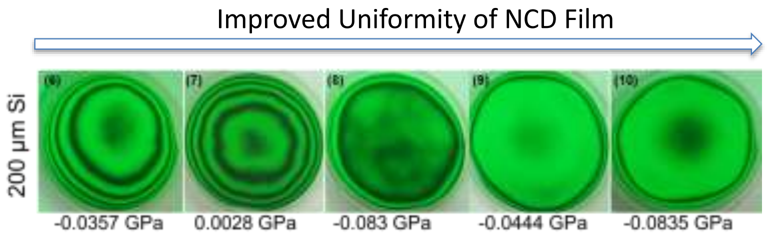
Advances in Diamond Integration

Top Side NCD Integration

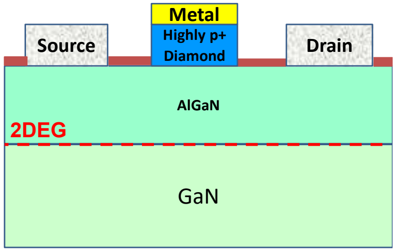


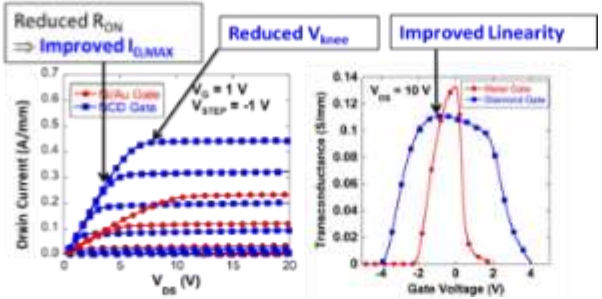


Low Stress, Uniform, Wafer-Scale Diamond CVD Growth

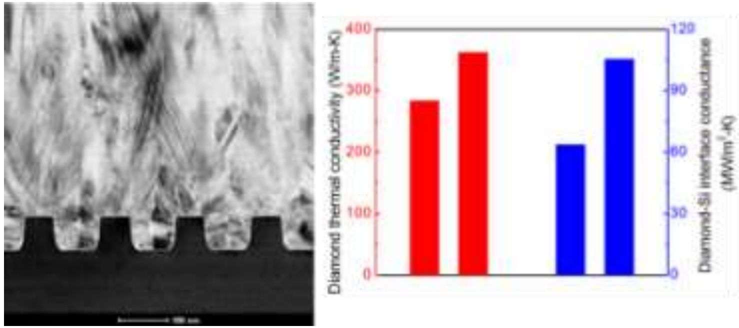


P-type Diamond Gate



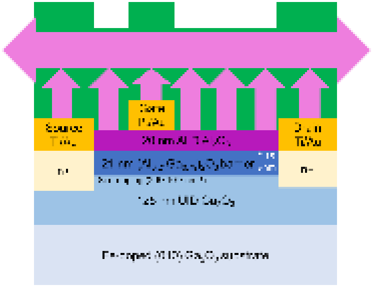


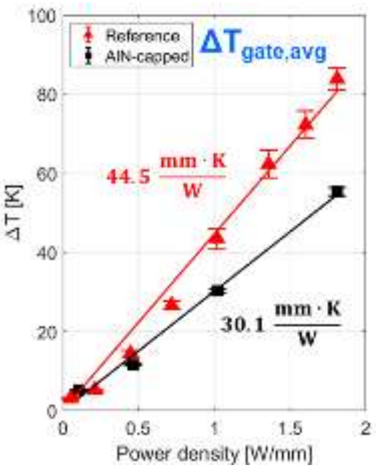
Improved NCD thermal conductivity by substrate nanopatterning OR seed size control



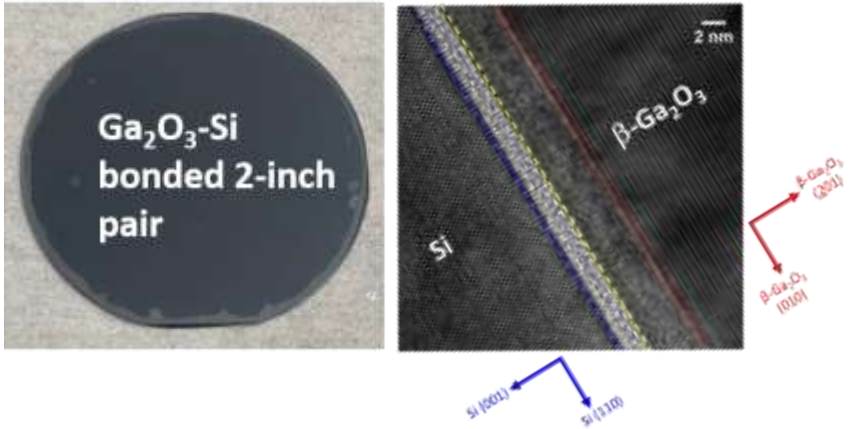
Thermal Management of Ga_2O_3 Electronics

AlN-capped Ga_2O_3 FET

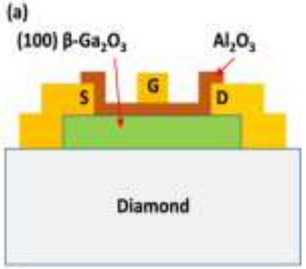


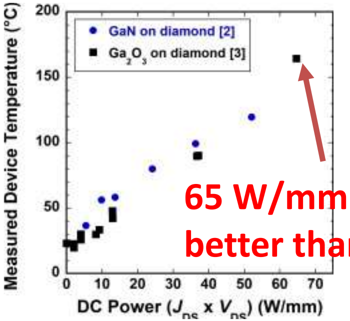


Surface-activated bonding of Ga_2O_3-Si

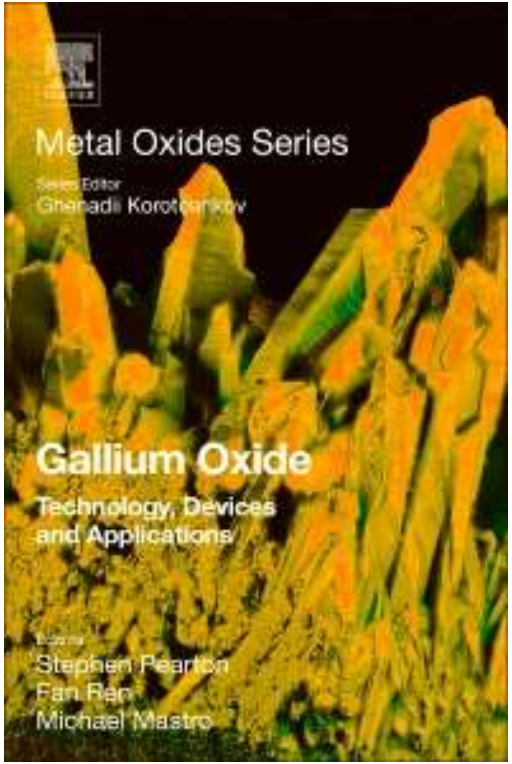


Exfoliated Ga_2O_3 transferred to diamond





65 W/mm DC, better than GaN!



Ga_2O_3 Book, 2018
UF and NRL

Topic 2: Vertical GaN Power Device Manufacturing

Vertical GaN for 5-20kV Power Switches

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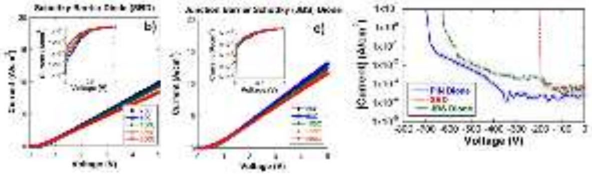
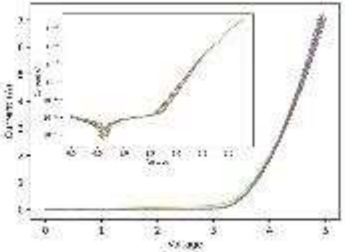
P-type Doping by Ion Implantation

Implanted PiN and JBS Diodes



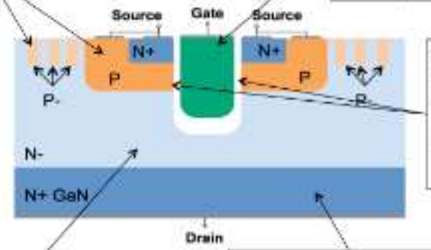
2” PiN Diode “pilot production”
1.2kV-6kV, 5-10A rating
(ARPA-E OPEN+ Program)



Challenges for any Vertical GaN Device

P-type Doping
- Selective area
- Controlled dose
- Low resistance contact

Gate Electrode
- Stable under electrical and thermal stress
- Appropriate work function for GaN/gate dielectric

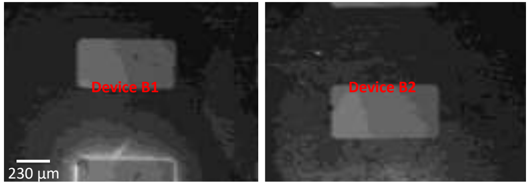


Gate Dielectric
- Conformal coating
- High k
- High E_{CR}
- Interface management

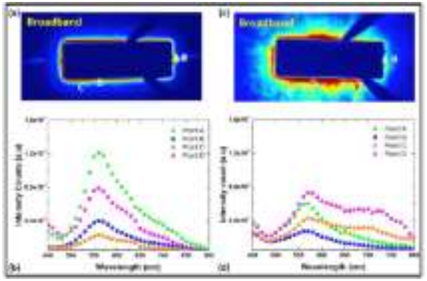
Drift Layers
- Low background doping
- Thick films
- High mobility
- Growth interfaces

Substrate
- Uniform N+ doping
- Low defect density
- Uniform offcut angle
- Back side contact

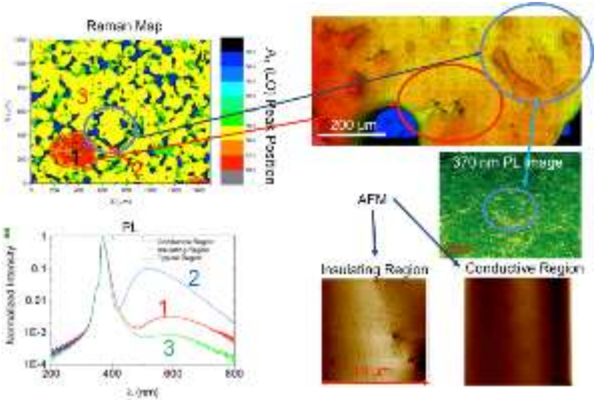
EL images – substrate effects



Hyperspectral Imaging of vertical diodes

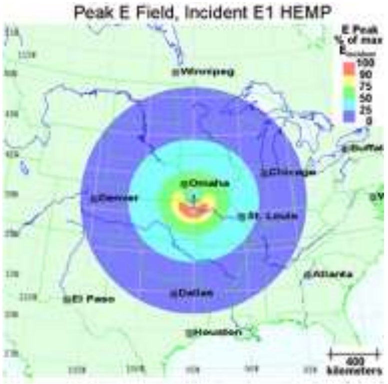


Substrate Characterization



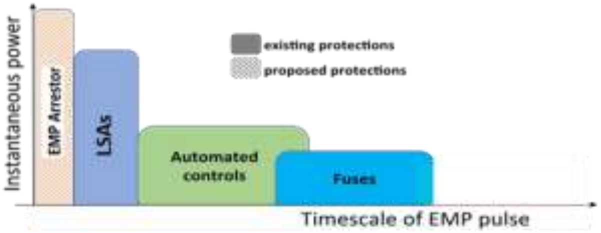
1.2kV and 3.3kV GaN Foundry

20kV GaN Electromagnetic Pulse Arrestor for Grid Reliability



➢ Transient protection is needed for MV grid-connected systems

➢ Electromagnetic pulses are a threat to the grid
- Very fast E1 component (< 1 ms)
- Unaddressed by current SOA technology (LSAs)



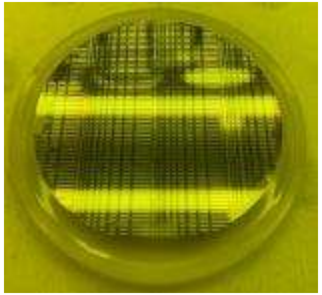
Sandia Epi

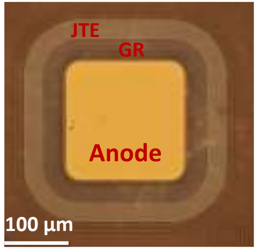
Sandia: Diode fab for MV grid protection	NRL/NIST: Foundry diode process
5 kV	1.2 kV
10 kV	3.3 kV
20 kV	6.5 kV

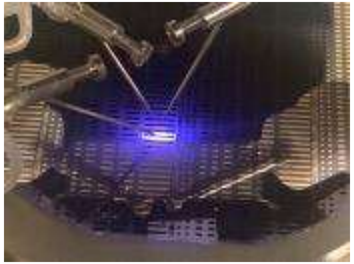
NRL/Sandia ARPA-E Program:
1.2-6kV PiN Diode Manufacturing
5-20kV PiN Diode Demonstration

1.2kV GaN Foundry

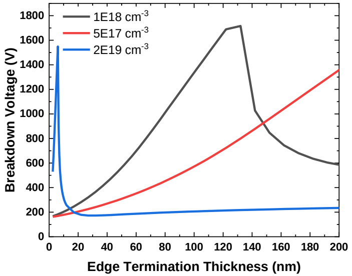
Wafer-Scale, Planar Device Process ("Pilot Production")

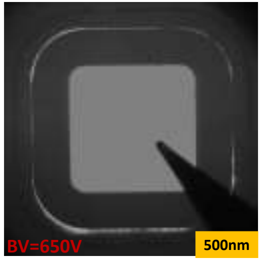


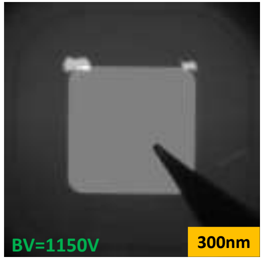




Edge Termination Simulation & Validation by EL





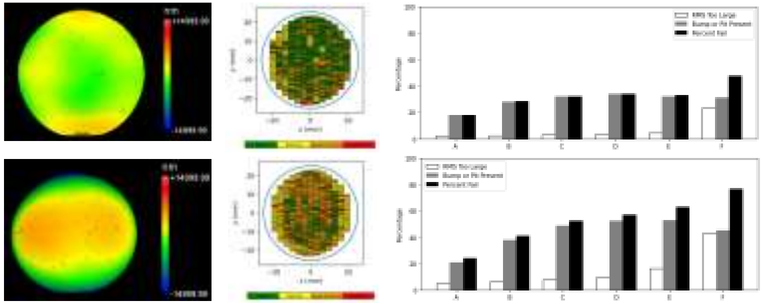


Incoming Metrology (Epi Pass/Fail)

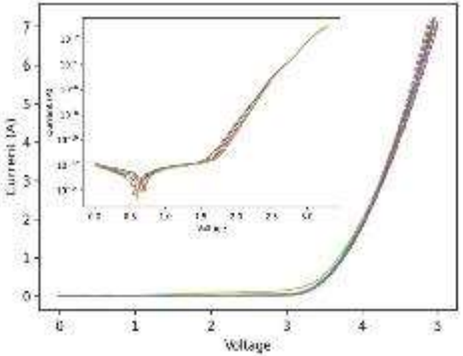
Raw Data

Device F Yield

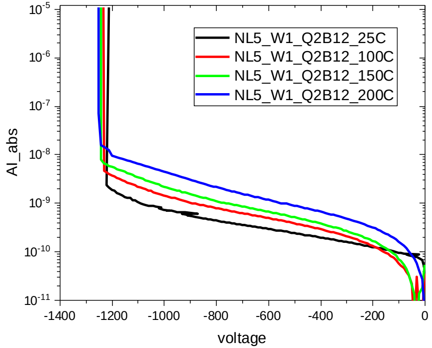
Failure Statistics



Forward I-V (>15A pulsed current)



Reverse I-V (>1kV w/ avalanche capability)



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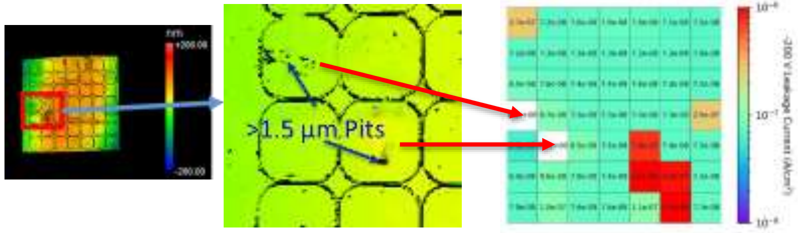
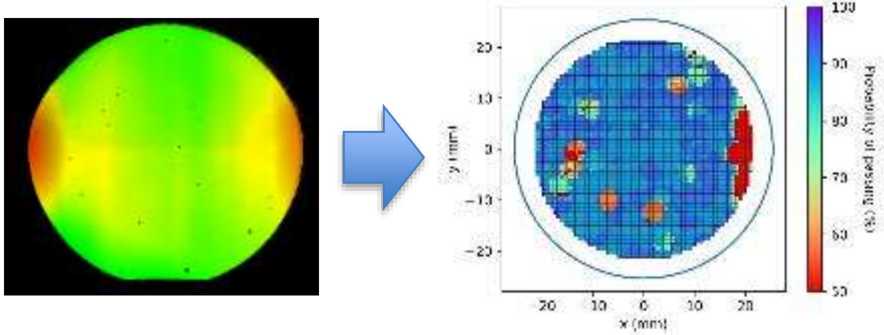
Next Steps: Machine Learning, 3.3kV Devices

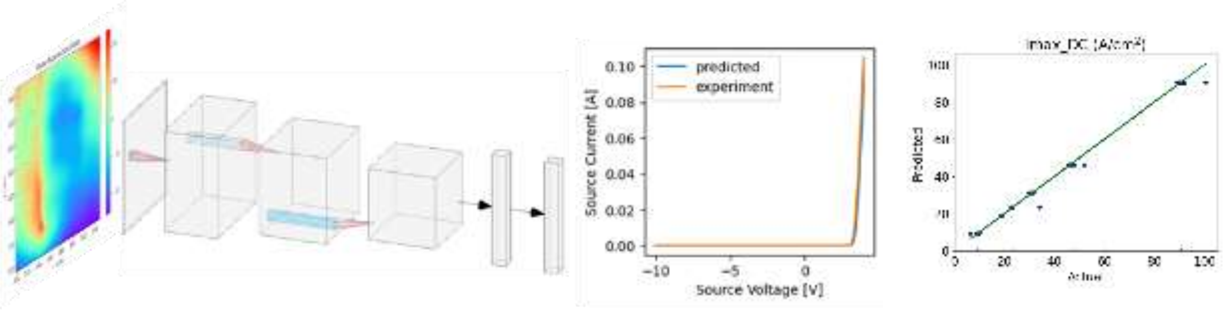
Correlation of optical profilometry to device performance



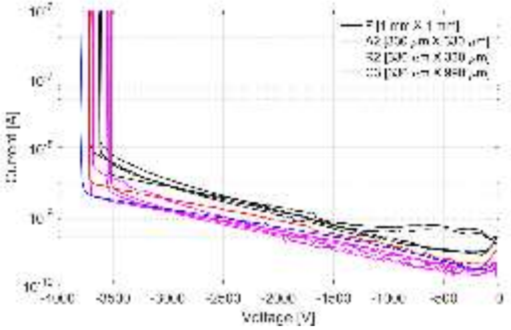
Incoming Wafer Screening & Yield Prediction Algorithms



Convolutional Neural Network to Predict Device Performance from Incoming Metrology



3.3kV-Class Device Demonstration



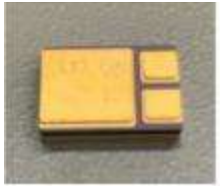
91% Accurate Predictions

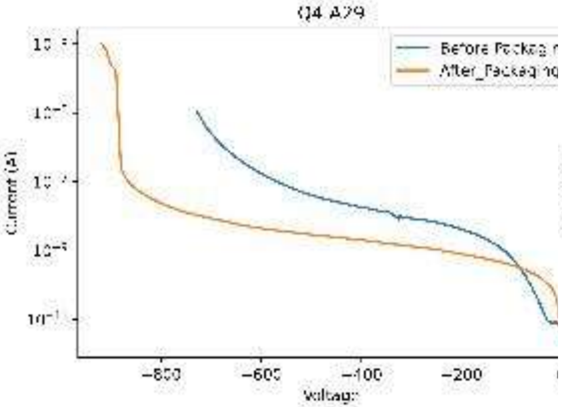
Packaging Development

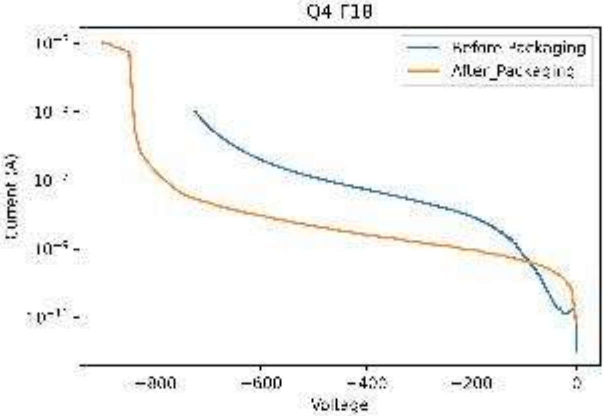
“A” Device
(16 bond wires)

“F” Device
(~64 bond wires)

- Kyocera surface mount package (standard part)
- Mounting and wire bonding completed at Integra (commercial source)
- Option for hysol encapsulation
- Package is ok for 1.2kV, evaluating viability for 3.3kV (limited by 0.03” gap between anode and cathode pads)

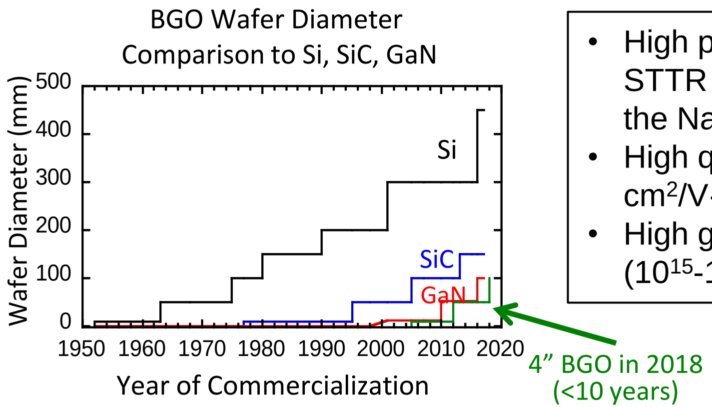




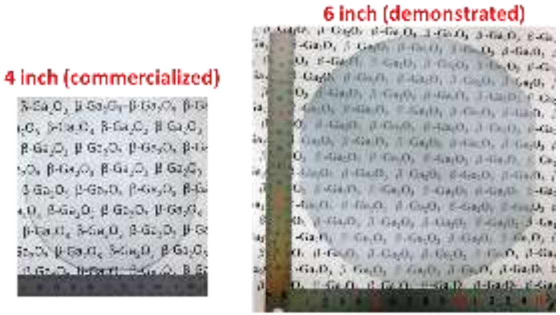


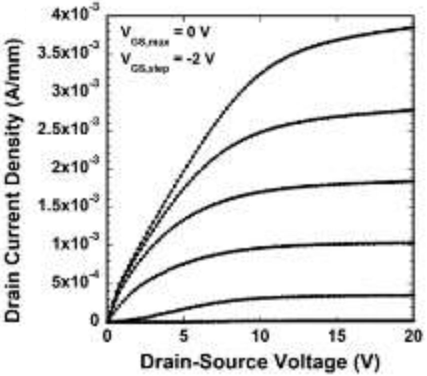
Topic 3: Ultrawide Bandgap Materials

Ga_2O_3 Materials Status/NRL Capability

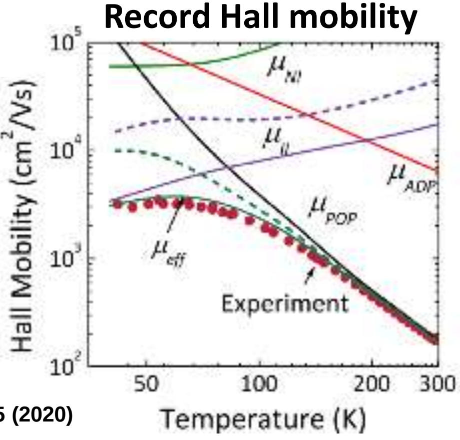


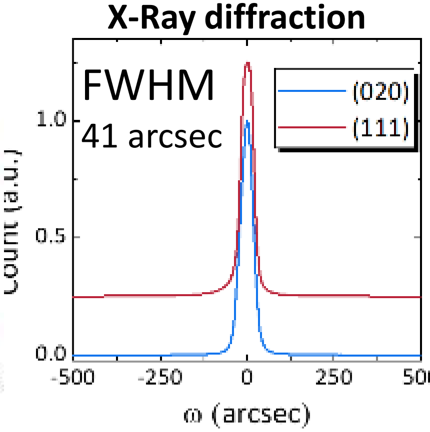
- High performance Ga_2O_3 MOCVD from ONR STTR (Agnitron Tech) uniquely developed for the Navy
- High quality Ga_2O_3 (record high mobility: 176 $cm^2/V\cdot s$ at RT
- High growth rate and n-type doping control (10^{15}-10^{19} cm^{-3})





Tadjer et al., J Phys D: Appl Phys 54, 034005 (2020)



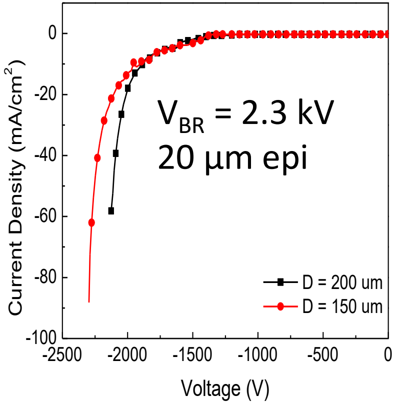


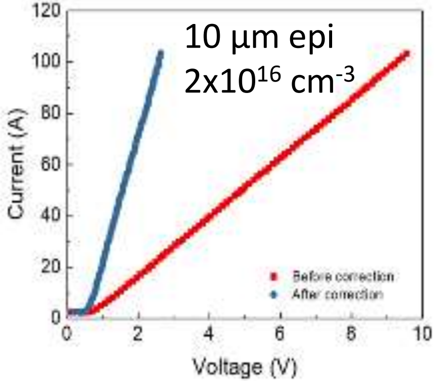
Zhang et al., APL Mater. 7, 022506 (2019).

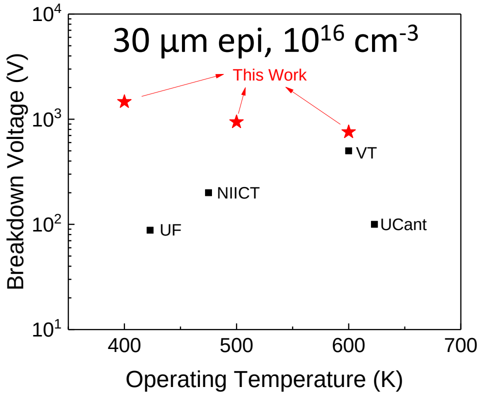
Recent Ga_2O_3 Device Demonstrations

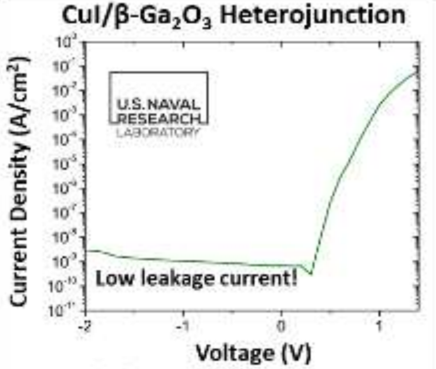
Vertical Devices

- Vertical Schottky diodes (collaboration with UF), first demos with epi thickness > 10 µm
- No possibility for p-type Ga_2O_3: need heterojunction p-n diodes (collaboration with UAB)





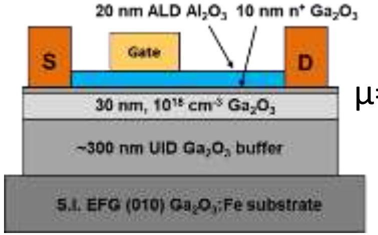




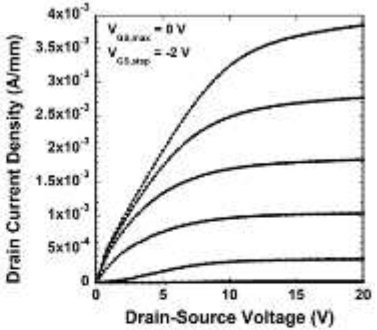
JC Gallagher et al., Appl Phys Express, 2019.
2019 Journal Spotlight Article.

Lateral Devices

First demonstration of Ga_2O_3 HFET via Agnitron's High Growth Rate MOCVD



μ=170 cm²/V·s

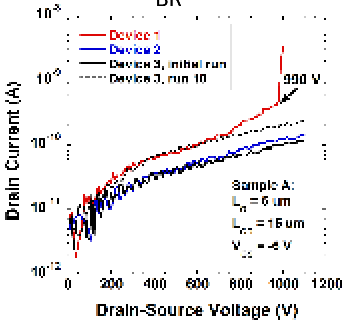


Tadjer et al., J Phys D: Appl Phys 54, 034005 (2020)

First demonstration of AlGaO/GaO HFET with Si delta-doping by O_3-MBE

Rsh (Ω/sq)	Mobility (cm²/Vs)	N_s (cm^{-2})
5857	95	1.12e13

V_{BR}>1kV



Tadjer et al., J Vac Sci Technol. A 39, 033402 (2021)

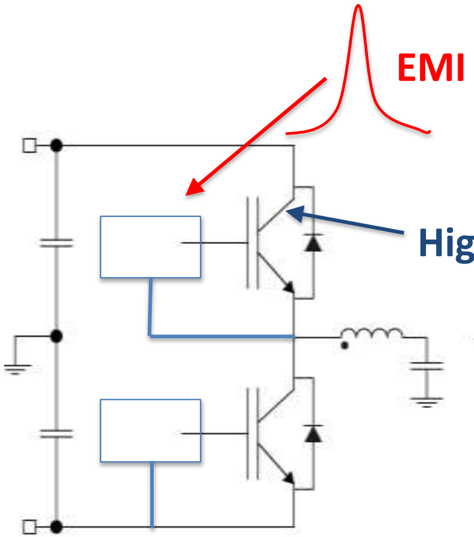
Topic 4: Optically Triggered Devices

EMI Issues

A **power system** cannot operate at >10 kV @ 500 kHz without a well-isolated isolated gate drive:

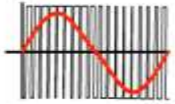
- Ultra-fast, high-power switching causes electromagnetic interference (EMI) → false triggering and/or failure
- Driving the gate of the high side switch is difficult, because it is referenced to high voltage node
- Optical isolation decouples the input from the output of the device

Example: Half-Bridge Converter

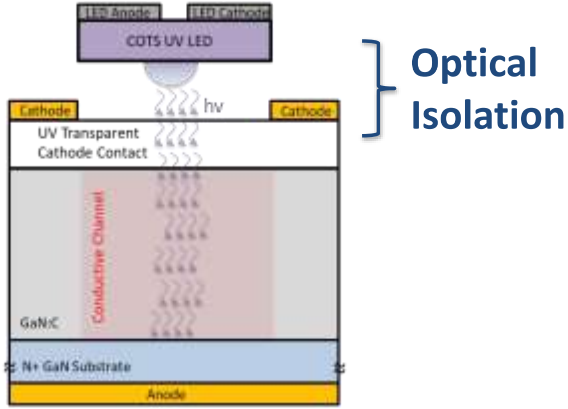


Sources of EMI:

- High *di/dt, dv/dt* switching
- Large motors
- Lightning
- Electromagnetic pulses



Example Solution:
Photoconductive Semiconductor Switch (PCSS)

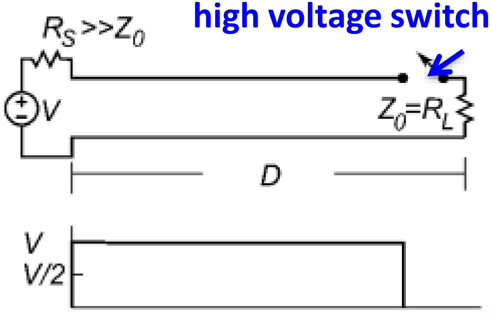


Optical isolation of the gate enhances resiliency and reduces complexity of power systems

Expected to be significant research topic (ARPA-E ULTRAFAST program)

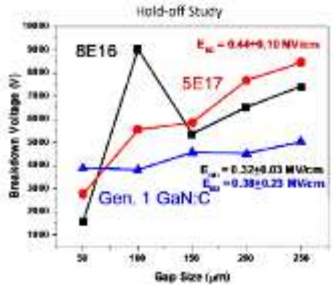
Photoconductive Switch Technology

PCSS Applications:
- Direct drive of solid-state HPM sources
- MVDC/HVDC Power conversion
- Wireless power transmission



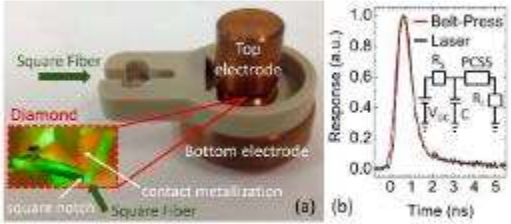
Advantages of PCSS:
- High voltage (tens of kV)
- High current (hundreds of amps)
- Direct drive (semiconductor laser)

Advantages of WBG PCSS
- 8kV blocking
- 10A/W Responsivity
- 16A Peak Current Demonstrates

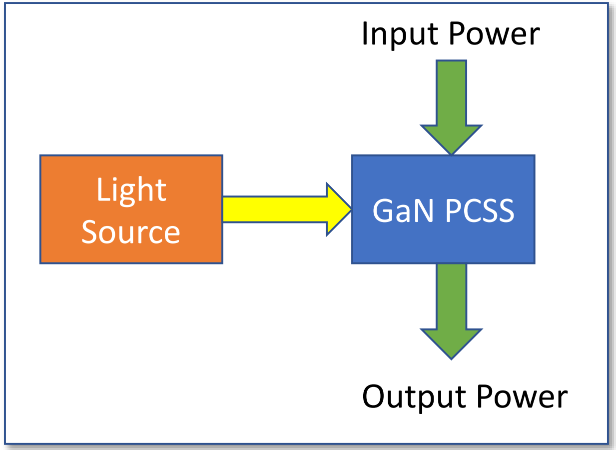


Devices:	Spark Gaps	Power MOSFETs	IGBTs	PCSSs
High Voltage	✓	✓	✓	✓
High Current	✓	✓	✓	✓
Low Rise Time	✓	✗	✗	✓
Low Jitter	✗	✗	✗	✓
High Rep Rate	✗	✓	✓	✓

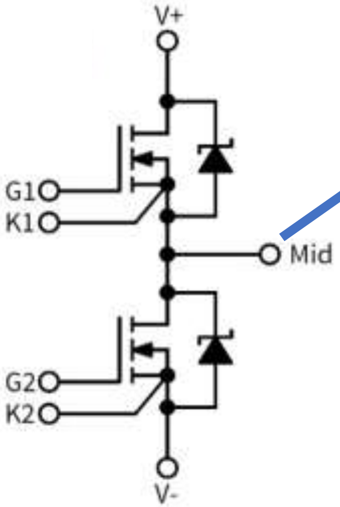
Photoconductive Switch with High Sub-Bandgap Responsivity in Nitrogen-Doped Diamond



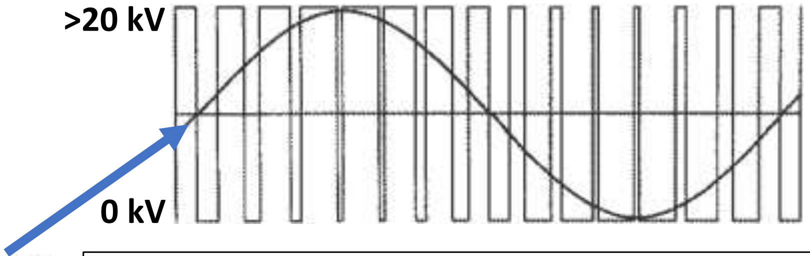
PCSS for Efficient Power Conversion



Half-Bridge Converter



Pulse Width Modulated Sinusoid



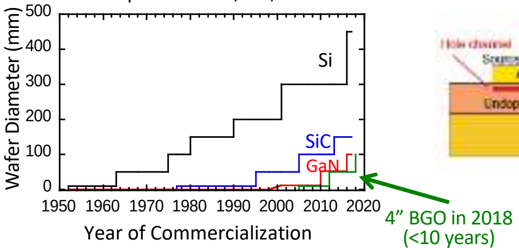
Example Application: PCSS Half Bridge Converter:

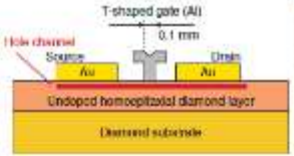
- Electrically isolated high side gate drive
- High voltage (>20kV)
- High Frequency operation (>100kHz)
- Reduced SWAP: Co-package PCSS with commercial off-the-shelf COTS Laser Driver

- Photoconductive Semiconductor Switch (PCSS) are optically triggered electrical switches, capable switching: multi kilovolt (kV), multi kiloampere (kA), at sub nanosecond (< ns) speed
- PCSS can be stacked in parallel and series to achieve virtually unlimited current and voltage capability
- Allow optical control of complex, high power switching circuits with electrically isolated drive
    - Robust high side gate drive: dramatically simplifies high side gate drive. PCSS prevents reference voltage swing.
    - EMI Rugged: Prevent false triggering under electromagnetic interference (EMI)

UWBG Technology Development Roadmap

BGO Wafer Diameter
Comparison to Si, SiC, GaN

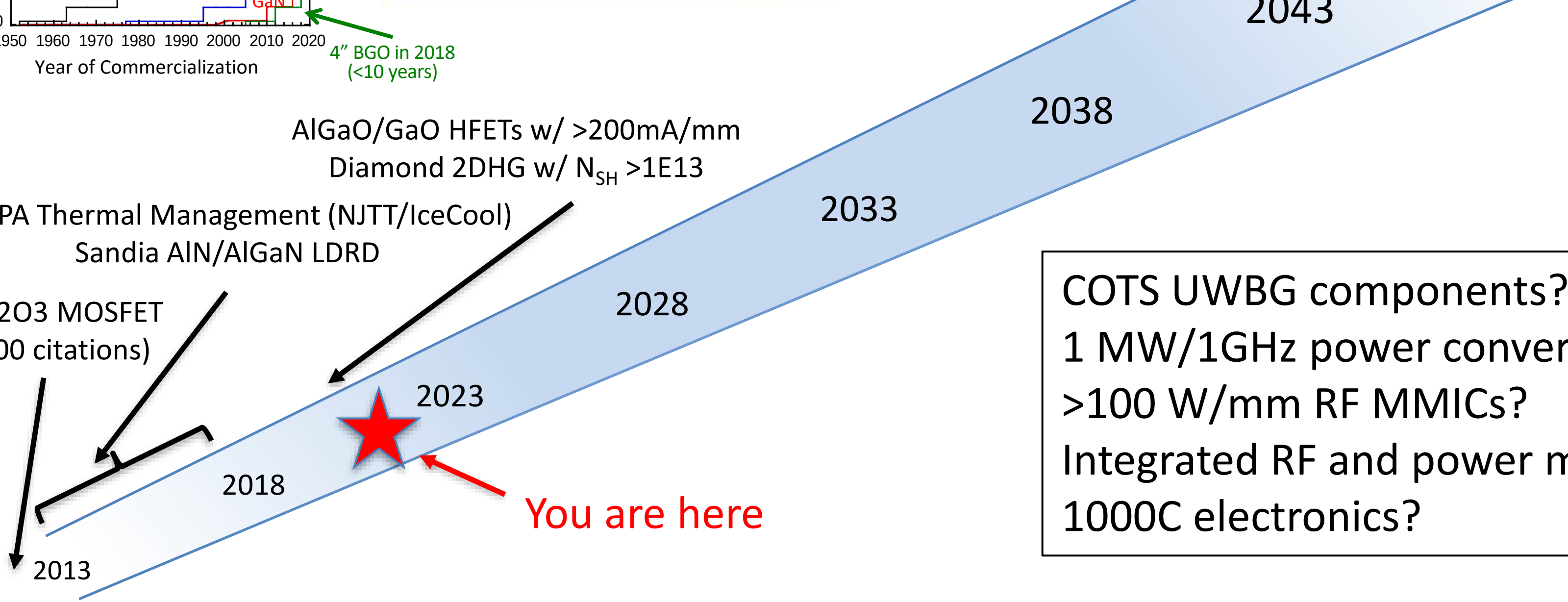




AlGaO/GaO HFETs w/ >200mA/mm
Diamond 2DHG w/ N_{SH} >1E13

DARPA Thermal Management (NJTT/IceCool)
Sandia AlN/AlGaN LDRD

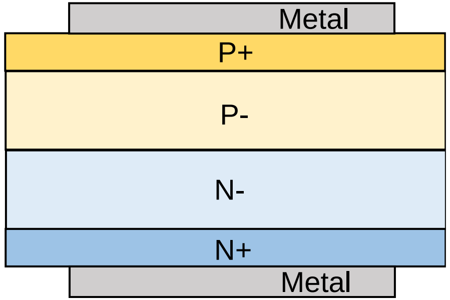
1st Ga2O3 MOSFET
(>1200 citations)

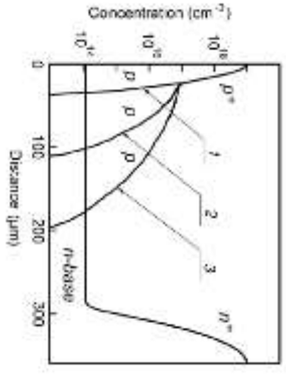


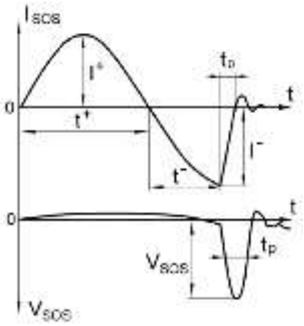
COTS UWBG components?
1 MW/1GHz power conversion?
>100 W/mm RF MMICs?
Integrated RF and power modules?
1000C electronics?

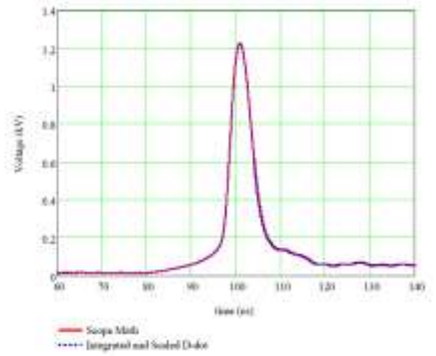
Si Technology R&D – Still Relevant!

Drift Step Recovery Diodes









Highly specialized diode structure

- Used in inductive storage circuits to generate high voltage nanosecond rise time pulses by exploiting the *Ldi/dt* effect
- Different operating space than typical power diode
- Need to store charge AND discharge quickly – typically mutually exclusive design criteria

Many potential applications in pulsed power circuits

- Short pulse radar
- Accelerators
- Medical
- Ignition
- Plasma processing
- Emissions control

SiC DSRDs are also of interest – smaller die, less stacking, more "snappy" switching

Summary

- Si R&D – still relevant!
- SiC devices are maturing, but still basic material work for >20kV and novel device opportunity
- GaN power devices are emerging and scaling to 5-10kV and >100A
- Ga2O3 technology is rapidly scaling – emerging opportunities
- AlGaN, AlN, and Diamond are emerging materials

Thermal Management is essential for ALL power semiconductor devices

- Near-junction temperature control in GaN devices
- Thermal management of Ga2O3 devices
- Increasing problem for WBG/UWBG devices – lower specific on-resistance → smaller die for same performance → increased power density

Advanced integration approaches are required to realize optimal performance at the system/module level

- Heterogeneous/monolithic integration of power switch and control circuitry
- Microfluidic cooling for thermal management
- Active interposer

Acknowledgments

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American Society for Engineering Education (ASEE)

Thank you for your attention!

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